For publication in the Instrument Society of America Transactions

* Submitted for Publication

23 p

A STABILIZED, AUTOMATED CAMERA FOR AIRBORNE ECLIPSE PHOTOGRAPHY

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ABSTRACT

The National Geographic Society and the Douglas Aircraft Company jointly sponsored the flight of a special DC-8 aircraft in the path of the solar eclipse of 20 July 1963 for the purpose of making coronal and related scientific observations. A twin camera was designed to take maximum advantage of the reduced sky background and extended observation time made possible by the high-altitude, high-speed flight. The camera, designed for good resolution and low internal scatter, was mounted on a two-axis, gyro-stabilized platform. The shutters were actuated by intervalometers, giving a programmed series of exposures on two types of film. Special treatment of the eclipse negatives brought out several interesting features of the corona.

INTRODUCTION

Although the solar corona can be studied at any time from the ground with the aid of a coronagraph, there are distinct advantages to observations at times of eclipse, and further advantages in making these observations from a high-flying aircraft. The image of the solar disk is, of course, occulted in a coronagraph, but the full solar radiance contributes to background sky brightness and to scattering into the measuring instruments. At times of natural eclipse, this background is reduced about

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10^6 times. The main advantages of a high-flying observatory are, first, a further reduction in sky background; second, an extension of the wavelength range over which measurements can be made; third, an extension of observing time achieved by flying along the eclipse path; and fourth, a reasonable assurance of good observing conditions, as one plans to fly above clouds and turbulence. The authors were thus very grateful for the opportunity to participate in the projected flight of a special DC-8 aircraft along the path of the eclipse of 20 July 1963, at an altitude above 40,000 feet.

Our particular experiment was concerned with the white light photography of the corona. The objectives were, first, moderate resolution, particularly in the polar regions where the curvature of polar rays yields information on the sun's general magnetic field; second, the observation of coronal features from the limb to as great a distance as sky background would permit; and third, photometry of the corona. The instrumentation requirements were thus moderate resolution optics free from internal scatter and multiple reflections, a combination of films giving resolution and latitude, a stabilized platform to permit relatively long exposures, and programmed, automatic shutter speed and film advance mechanisms to make optimum use of the duration of totality.

Because the design of the instrumentation was not begun until January 1963, it was not until May that the major camera components were present for assembly. The remaining two-month period for construction, assembly, and testing was too short, and certain undesirable factors remained in the "finished" camera on the eclipse date. In spite of this and other difficulties, most of the experimental objectives were achieved.

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It is the purpose of this paper to describe the instrumentation and to discuss its performance in the light of the results obtained.

OPTICS AND PHOTOGRAPHY

The requirements of moderate resolution and low internal scatter were well met by a Kilfitt f/5.6, 600-millimeter single element (cemented doublet) achromatic lens. Previous tests of multiple element lenses and reflector-type systems showed large amounts of internal scatter which were not present in this single element lens.

A twin camera was designed in order to experiment with a radial density filter (described below) in one film plane. To utilize fully the corrected field of the lenses and to record the corona out to 10 solar radii, 70-millimeter film with a 51-millimeter frame diameter was required. Two commercially available 70-millimeter magazines with electric film advance were rebuilt to eliminate a nonuniform back reflection from their film plates. To minimize internal scatter, the lens mountings and internal baffling were designed to keep all diaphragm edges from intersecting bright portions of focused beams. The lenses and magazines were assembled as shown in Figures 1 and 2 into the gimbal of a two-axis stabilized platform. To make film advance and exposure time variation fully automatic, two shutter control intervalometers (described below) were used with the modified magazines.

The completed camera was focused by taking exposures of the moon. These negatives indicated a resolution of about 6 arc-seconds on High Contrast Copy Film with the lens stopped down to f/8. Later tests on an NBS test chart indicated 4 seconds of arc.

Two types of film were used in each magazine. Plus-X Negative was chosen because of its speed and long scale, while High Contrast Copy Film was used to provide higher resolution over restricted coronal regions. Since a commercial film splicer of the correct size was not readily available, the two films were strongly spliced together with 1-1/4-inch-wide polyester film tape. A small perforation before the splice actuated a microswitch installed in one magazine, automatically shifting the shutter control from the intervalometer for one film to that for the other. The intervalometer settings for Plus-X Negative were 0.08, 0.16, 0.32, 0.64, and 0.80 second. The exposure time sequence for High Contrast Copy Film was 0.20, 0.40, 0.80, 1.6, and 3.0 seconds.

The entire corona cannot be obtained in a single exposure of these films because of the steep coronal brightness gradient shown in the upper curve of Figure 3. The radial extent of the corona for each programmed exposure time (shown for the Plus-X Negative exposures in the step graph at the bottom of the figure) was determined from the coronal brightness data of H. C. van de Hulst[1] and D. E. Blackwell[2] and the characteristic curves[3] of the film. (References (1) and (2) use the average brightness of the solar disc which is closely 10^{10} ergs/cm^2-sec-steradian in the panchromatic region 3600 - 6500 Å.) Levels (A) and (B) in Figure 3 indicate the approximate background sky brightness ("skyshine") for ground and airborne observers. Plotted in the center of the figure is the expected flux to the film ($F_F(r)$ in ergs/cm^2-sec) which was calculated from the coronal brightness ($F_c(r)$), the f value of the lens (f/8), and the various transmissions (T) through the equation

$$F_F(r) = \frac{\pi}{4}\left(\frac{1}{f/8}\right)^2 T_{lens} T_{window} F_c(r)$$

If a useful range of negative density (D) is assumed to be from 0.4 above fog to about 2.2, and the energy per unit area ($E_{(D)}$) of reference (3) is assumed necessary to produce these densities, then the simple calculation

$$\frac{E_{(D)}}{t} = F_F(r)$$

allows estimation of the radial extent for each exposure time (t) from the curve of $F_F(r)$. Exposures were selected, within the restrictions of shutter operation and camera stabilization, to cover the radial extent of the corona as fully as possible.

To reduce the effect of the steep coronal brightness gradient, a radial density filter was made on Fine Grain Positive film for use in one camera. A negative image, 10 times the desired size of the filter, was made by rotating a disc with a radially increasing aperture in the film plane of an enlarger. The aperture ($\Delta\theta(r)$) in the disc was cut from the relations

$$\Delta\theta(r) = 2\pi T(r) , \qquad T(r) = \frac{F_D(r)}{F_F(r)}$$

where $F_D(r)$ is defined by the straight line tangent to the curve of $F_F(r)$ in Figure 3. The resulting positive is densest inside the solar limb and allows a useful exposure into and even beyond the limb in most cases. The final radial transmission was 9/10 T(r) above because of the 10-percent absorptance of the film base. Transmission of the filter was determined by densitometer readings of a contact positive made from the large negative. A 10:1 reduction of a satisfactory negative produced the final radial density filter, which was mounted just before the film plane of the left camera. The mechanical alinement of the filter with the axis of the 8-power pointing telescope was accomplished by boresighting the left camera and telescope on a distant light.

Many step-wedge exposures of the two film types employed were processed in different developers in preparation for the processing of the approximately 100 eclipse negatives. Each basic eclipse exposure was developed normally, was overdeveloped, and underdeveloped to provide a fine variation of film speed and contrast. A two-step developer, Diafine, increased the scale of the High Contrast Copy Film. Other developers had only a small effect on this film. The effects obtained from varied development of the Plus-X eclipse negatives at 68° F are noted in Table I.

TABLE I.- EFFECT OF VARIOUS DEVELOPMENT TECHNIQUES ON PLUS-X NEGATIVES AT 68° F

Developer	Time	Use
D-76 (1:1)	12 min	Normal development
D-11	12 min	Overdevelopment of shorter exposure extends large streamers with some "blocking up" of fine detail
D-76 (1:1)	6 min	Underdevelopment of longer exposures produces a thinner, "crisper" negative; enhances fine detail by reducing background

The standard DC-8 window was replaced by an available window made of choice borosilicate crown glass, 1-1/4 inches in thickness, with no bubbles larger than 1/10 millimeter within its 12-inch diameter. The surfaces were ground and polished to better than 6 wavelengths. The outer surface was coated to give 1.0-percent reflection and the inner surface 0.6-percent reflection over a 400-675mμ range. The window was mounted normal to the expected line of sight (48.5° elevation) in the specially recessed cylindrical frame visible in Figure 2. Around the inside edge of the frame were many small orifices from which dry nitrogen could be pumped to purge the inner window surface of condensation. Finally, a 1/2-inch-thick, removable plexiglass disc was fitted across the inner window surface. The plexiglass cover was intended to be opened for the eclipse and other observations, but was to be closed for the remainder of the flight to conserve nitrogen.

CAMERA SHUTTERS AND INTERVALOMETERS

The camera shutters and intervalometers were designed to give a wide selection of automatic, programmed exposure times and a minimum inertial impulse to the camera. Each shutter consisted of a disk with a fixed angle sector opening. To minimize inertial inputs, the disks were made of 0.010-inch sheet aluminum, skeletonized, and covered with 0.001-inch aluminum foil. Each disk was driven by a constantly running, governor-controlled motor, through a clutch and detent device. The two systems were counterrotating.

The shutters were actuated simultaneously through their clutch and detent devices by signals from an intervalometer. Each of two intervalometers put out a repeated series of five pairs of "open-close" pulses. Only one intervalometer was in use at a time, being matched to the type of film in the camera. The switch to the second intervalometer was triggered by the momentary closing of a microswitch through a notch in the film near the splice.

Each intervalometer was made up of a synchronous motor (110 v a.c., 60 c/s) driving a timing cam shaft, which, in turn, drove a distributor cam shaft at a 5:1 reduction ratio. Any one of 50 separate gear assemblies available from the manufacturer could be inserted between the motor and the timing shaft to give a possible range of timing shaft speed from one revolution per 0.66 second to one revolution per 6 seconds. Each cam was adjustable to actuate switches so as to give from 2 to 98 percent "on" time per revolution. A large selection of exposure times could thus be programmed into the intervalometer. The film advance mechanisms of the camera were simultaneously pulsed by a switch on the timing shaft, following the "close shutter" signal. Finally, external switches were available to lock out the automatic system and operate the shutters and film advance at will.

STABILIZATION

Through a special gyro system, it was expected that the entire aircraft would be stabilized for the period of the eclipse to within $\pm 1/4^{\circ}$ in roll and yaw, and considerably better in pitch. The frequency of pitch motion was unknown. The vibration amplitude inside the aircraft cabin was known to be less than 3×10^{-4} inch.

Because of limited time, funds, and aircraft space, the camera was mounted on a two-axis (rather than three-axis) gimbal platform, manufactured by Power-Tronic Systems, Inc., which had a quoted capability of maintaining stable pointing to within 2 arc seconds with a load of up to 150 lb. Because the motion of the aircraft was expected to be least about the pitch axis, this axis of the platform was left uncorrected.

Two precision integrating gyros were used to provide the correction signals to the platform torquers. These gyros have a negligible drift for short durations, are quite sensitive, and were particularly easy to trim for compensation of earth rate. These characteristics proved particularly important to the experiment, as follows.

First, integrating gyros "remember" any angle through which they turn, and are thus able to recover precisely from sharp impulses. In spite of the precautions outlined in the previous section, the shutter action gave such undesirable impulses to the system. Second, there was little time for gyro drift during the eclipse. Third, it was necessary to trim the gyros for earth rate compensation at the last minute before totality, because on all previous flights air traffic problems, delays, and cross winds had prevented orientation of the aircraft to bring the sun within the pointing range of instrument.

Amplifiers to match the gimbal torque motors were separately purchased. A block diagram of the gyro control system is shown in Figure 4. The final camera load for the torquers was between 70 and 85 pounds. Final test of the stabilization system showed that the gimbal was torque limited at a very low frequency. This was satisfactory for compensation of aircraft motion, but actuating the camera shutters caused a sharp inertial input that the system could not correct in less than about 0.025 second. There was insufficient time before the eclipse to remove this input, for example by changing the location of the shutters. It was therefore decided to reduce the photographic effect of the impulse by doubling the exposure times and stopping down the lenses from f/5.6 to f/8. Furthermore, the shortest exposures (0.02 and 0.04 sec) were deleted from the program. This last change tended to emphasize exposure for the mid-corona.

During totality, the corona was observed through an 8-power viewing telescope mounted on the camera. A slow and repetitive horizontal motion of the image was observed, along with a momentary vertical motion when the shutters operated. During periods when the shutters were not operative, the camera pointing accuracy was 10 arc seconds or better in the vertical (roll) direction. The N.O.T.S. kymograph record[4] indicates that during totality the average amplitude of aircraft roll was about ±8 arc minutes.

CAMERA PERFORMANCE AND PRELIMINARY RESULTS

The experimental objectives of obtaining adequate coronal resolution and wide latitude were satisfactorily achieved. The negatives have not been analyzed to measure the total coronal brightness because an unexpected source of random scattering was present. On the actual eclipse flight, moisture inside the DC-8 cabin condensed on the inside surface of the optical window whenever the protective plexiglass cover was removed. This was totally unexpected since on all the trial flights at similar altitudes, the flow of nitrogen across the window surface had been sufficient to prevent condensation. After two unsuccessful attempts at leaving off the plexiglass, it was finally secured in place 2 minutes before totality. The condensation evaporated just as totality began. The plexiglass introduced several double reflections and produced irregular scattering over the negatives, but did not degrade resolution quite as much as might have been expected.

The small image size and limited resolution, coupled with the large coronal density range, made reading and working directly with the negatives and/or trial enlargements rather difficult. The situation was remarkably improved by the use of a new type of contact printer, the Fluor-O-Dodge. In this device, lower density regions on a negative are given reduced printing exposure through the quenching of the phosphorescent light source by infrared radiation. This process follows very closely the spatial pattern of density in the negative. A variation of this process may be used to enhance the density step along moderately well defined density edges of the negative. Both processes (dodging with and without edge enhancement) were used on our negatives with considerable improvement in clarity.[1] The dodged negatives could be enlarged up to 13 times.

As was expected, the radial density filter blurred out the finer coronal detail, but it did allow large bright features to be traced inward to the lunar edge. Some information on the aircraft motion has been obtained from analysis of the pictures taken with the radial density filter. When the camera was incorrectly pointed, the limb of the moon was off-center on the filter and only a thin narrow crescent of the bright inner corona could expose the slower film. About 0.8 sec was required to expose this crescent through the filter. On the longest exposures, two and sometimes three such crescents were observed at the east and west limbs of the moon (Figure 6). These crescents, present on six out of seven of the 3-second exposures, represent the extreme limits of a periodic horizontal motion of the camera during the exposure. As the camera was stabilized to eliminate the effects of aircraft roll and yaw, this motion must have been the component of aircraft pitch in the film plane. The average full displacement of 0.02 inch may be easily measured on the negatives. This displacement corresponds to an average amplitude of 1.5 minutes of arc motion of the film plane, with a time period somewhat greater than

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[1]We are grateful to the Sacramento Peak Observatory for permission to use their Fluor-O-Dodge, and, in particular, to Mr. Jerry Loomis who helped us operate the equipment.

2 seconds. The corresponding average amplitude of aircraft pitch was then 2.0 minutes of arc. This result indicates that the small amplitude, 1/2 to 1/4 c/s motions on the N.O.T.S. kymograph record of superimposed pitch and yaw motion of the aircraft,[4] was predominantly due to aircraft pitch.

The major causes of loss in resolution have been estimated from a further evaluation of the camera after the eclipse. These tests were made with 1000:1 contrast NBS test charts at a distance of 38.5 times the lens focal length. To evaluate separately the several contributing factors, exposures were made with internal (camera) and external (non-camera) shutters, with the camera stabilized and fixed, and with and without the plexiglass cover. Because many of the actual conditions cannot be reproduced in the laboratory, this evaluation is only approximate. For example, the resolution varies across the surface of the plexiglass cover from 6 to 60 seconds of arc as a result of scratches incurred while opening and closing the cover. The region used here for evaluation is that region approximately before the right lens during the eclipse. The data for the contribution from pitch motion are derived from an analysis of a 1.5 minute of arc amplitude, 1/2 c/s undamped sine wave, and represent the angular motion of the camera during the various exposure times. The net resolutions, given in Table II, are based on the assumption that the angular resolutions of the various components are roughly additive. The net resolution derived from this evaluation is consistent with the 35-45 seconds of arc measured on the Fluor-O-Dodged positives of the shorter exposures. The resolution in the horizontal plane of the camera was reduced about equally by the plexiglass and by the pitch motion, while the vertical resolution was reduced predominantly by the shutter impulse.

During totality, 96 exposures were made. Fluor-O-Dodged positives are reproduced in Figure 6 (some detail and range have been lost in the reproduction process). On the negatives, three major streamers may be seen as far out from the center of the sun as 5.7, 6.0, and 6.5 solar radii. Polar rays may be traced on the less exposed negatives to about 2.3 solar radii, while on the longer exposures they may be seen terminating at about 2.6 solar radii. The polar rays broaden with increasing radial distance. Some indication of a fine "doublet" structure of the rays is present but the resolution is insufficient to determine whether this is a true coronal characteristic or just a projection and blur effect.

The point of intersection of lines drawn tangent to the polar rays is a parameter descriptive of the geometry of the general magnetic field.[(5)] From an analysis of the preliminary enlargements, this point appears to be at about half the distance to the point where the tangents were drawn. This value, which corresponds to neither a radial nor a dipole field geometry, is consistent with previous coronal observations. More accurate enlargements are yet to be made to refine the determination of this parameter from our several photographs.

CONCLUDING REMARKS

In spite of the presence of several deterring factors, coronal features have been traced to large distances from the limb and useful information on the polar rays has been derived. Three important modifications to the equipment should improve its resolution by an estimated factor of four. Reduction of camera weight and installation of another gyro for the third axis will greatly improve stabilization. Shutter impulses can be eliminated by locating the shutter either at the intersection of the stabilization axes or completely outside the camera. An increased nitrogen flow across the window is highly desirable, and replacing the plexiglass cover with coated optical glass would be a prudent safety factor. With these improvements, changes in coronal geometry can be accurately monitored throughout the solar cycle by means of high-altitude (airborne) eclipse photography.

ACKNOWLEDGMENTS

Patience and cooperation are put to a severe test whenever a project is faced with short deadlines. The authors wish to express their gratitude to the many individuals whose help contributed to the success of the experiment.

In particular, we wish to thank Dr. N. G. Roman and Mr. E. J. Ott, of NASA Headquarters, for prompt approval and financial support of the project; Mr. A. Gasser, who procured the Kilfitt lenses; and Mr. W. G. Ogles, for his help with photographic techniques. Above all, we thank the Douglas Aircraft Company personnel for their hard work, patience, and cooperation during all phases of the project.

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(2) D. E. Blackwell, A Study of the Outer Corona from a High Altitude Aircraft at the Eclipse of 1954, June 30, Royal Astron. Soc. Monthly Notices 115, p. 629, 1955.

(3) Films in Rolls for Black and White Photography, Kodak Pub. No. F-13 (7-62), Rochester 4, N. Y.

(4) Project APEQS, Douglas Report No. G-36439, Sept. 1963.

(5) H. C. van de Hulst, On the Polar Rays of the Corona, B.A.N. 11, 410, 150, 1950.

TABLE II.- APPROXIMATE RESOLUTION COMPONENTS (SECONDS OF ARC)

	Film plus lens	Pitch motion: Exposure time, sec	Pitch motion: Probability	Pitch motion: Motion (M)	Shutter	Plexiglass plus window	Net resolution (R)
Horizontal meridian	PXN 9	0.08	0.32	$11 > M > 1$	---	15	$35 > R > 25$
			.68	$23 > M > 11$			$47 > R > 35$
		.16	.32	$22 > M > 3$			$46 > R > 27$
			.68	$45 > M > 22$			$69 > R > 46$
		.32	.32	$41 > M > 11$			$65 > R > 35$
			.68	$98 > M > 41$			$22 > R > 65$
Vertical meridian	PXN 9	---	---	---	25	9	43
Horizontal meridian	H.C.C. 4	.20	.32	$30 > M > 7$	---	15	$49 > R > 26$
			.68	$70 > M > 30$			$89 > R > 49$
		.40	.32	$60 > M > 20$			$79 > R > 39$
			.68	$140 > M > 60$			$160 > R > 79$
Vertical meridian	H.C.C. 4	---	---	---	25	9	38

FIGURE LEGENDS

Figure 1.- Twin lens eclipse camera.

Figure 2.- The camera installation aboard the aircraft.

Figure 3.- Log coronal brightness and estimated exposure ranges. (Level A: "Skyshine" at mid-totality for a ground observer in panchromatic region. Level B: "Skyshine" at mid-totality at 42,000 ft in panchromatic region as deduced from reference 2.)

Figure 4.- Basic block diagram of gyro control system.

Figure 5.- Three-second exposure through radial density filter on High Contrast Copy Film.

Figure 6.- Solar corona, 20 July 1963.

Figure 6(a).- 0.16-sec exposure; normally developed negative; print Fluor-O-Dodged with edge enhancement.

Figure 6(b).- 0.32-sec exposure; underdeveloped negative; Fluor-O-Dodged print.

Figure 6(c).- 0.16-sec exposure; overdeveloped negative; Fluor-O-Dodged print.

Figure 6(d).- 0.64-sec exposure; underdeveloped negative; Fluor-O-Dodged print.

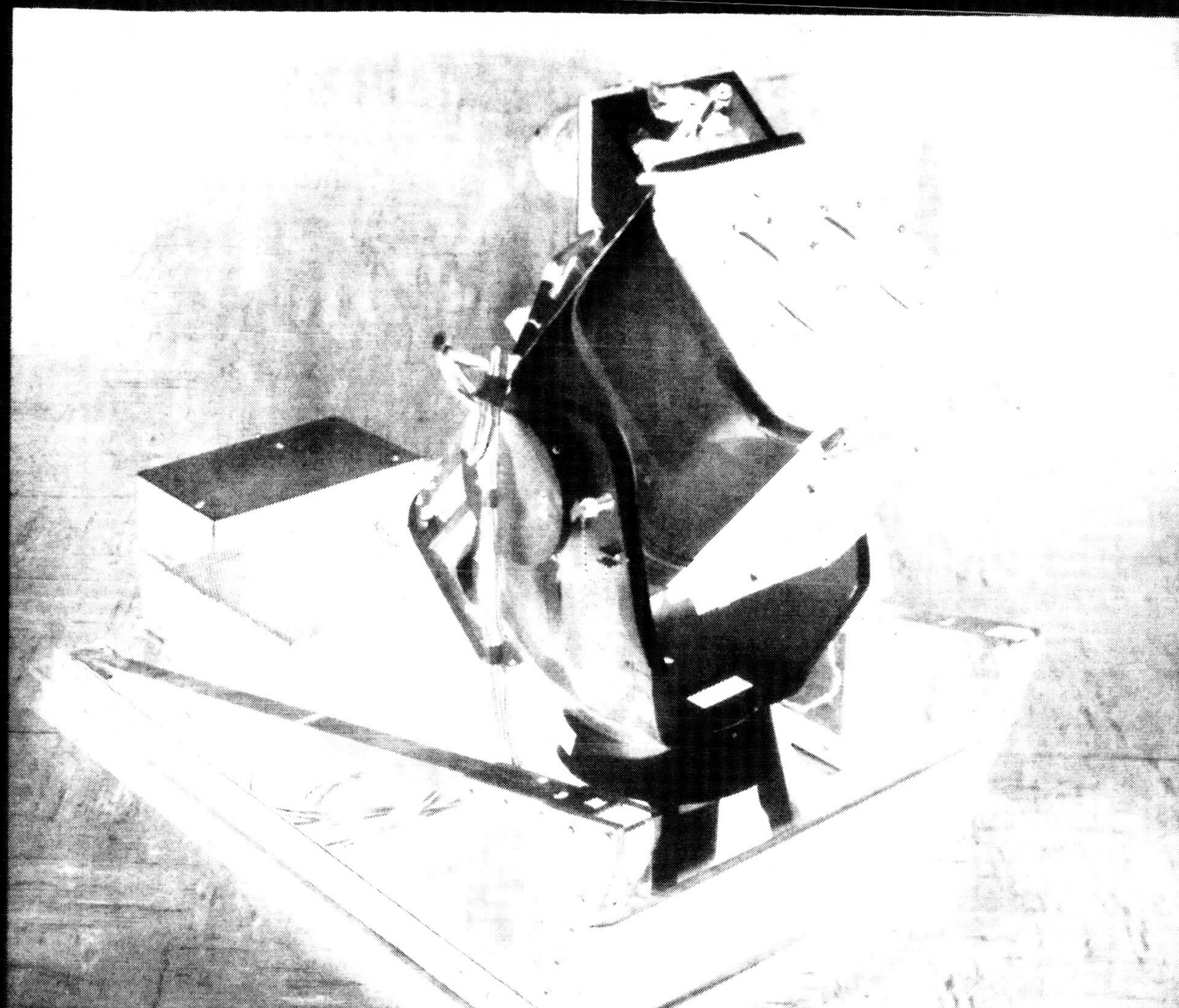

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Figure 1.- Twin lens eclipse camera.

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Figure 2.- The camera installation aboard the aircraft.

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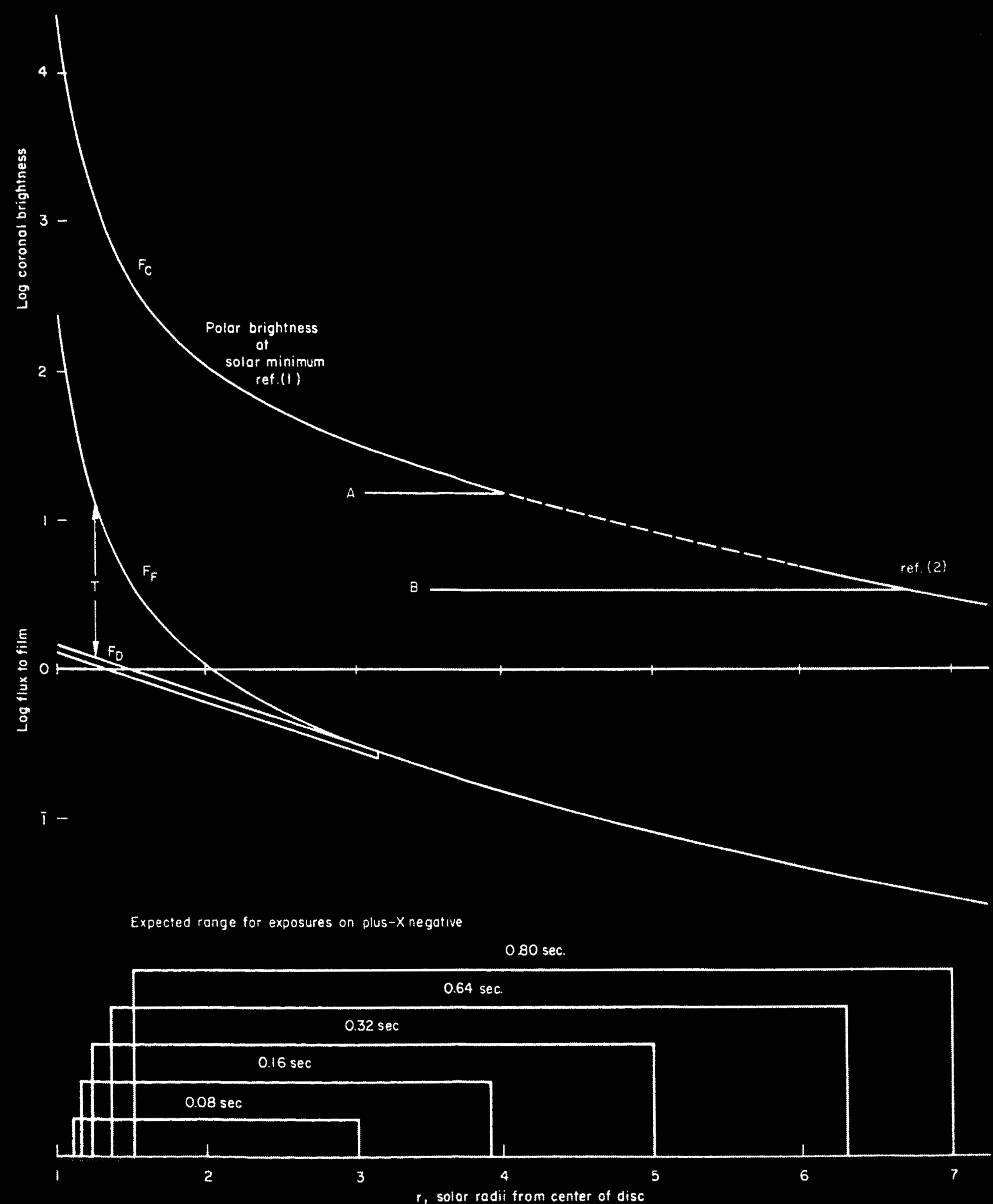

Figure 3.- Log coronal brightness and estimated exposure ranges. (Level A: "Skyshine" at mid-totality for a ground observer in panchromatic region. Level B: "Skyshine" at mid-totality at 42,000 ft in panchromatic region as deduced from reference 2.)

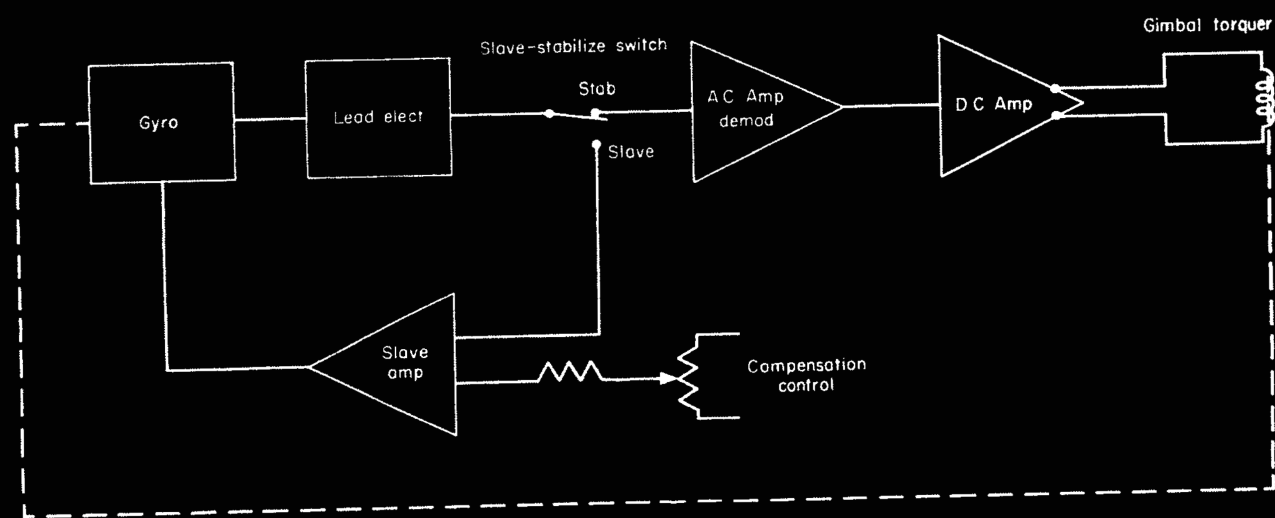

Figure 4.- Basic block diagram of gyro control system.

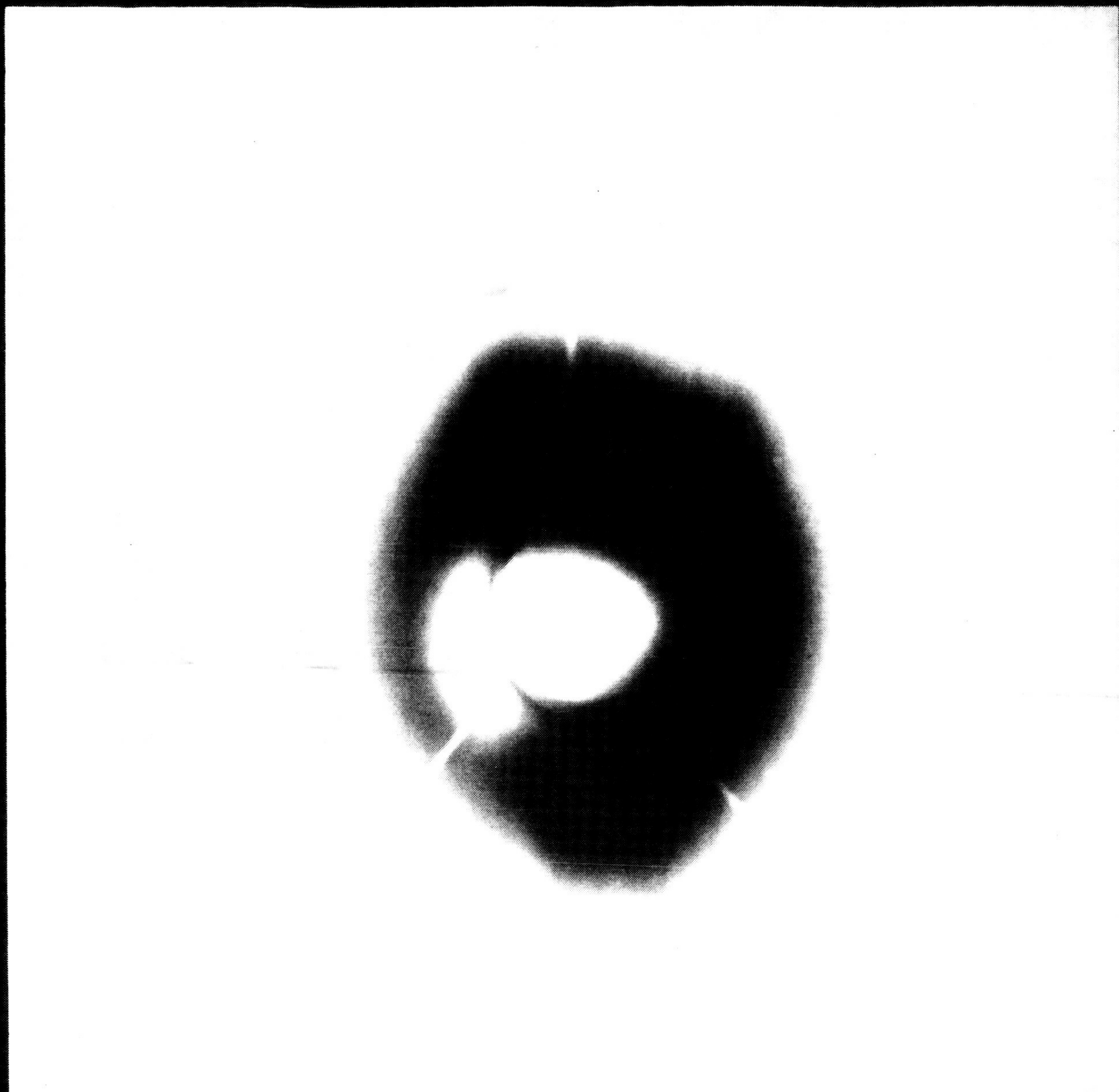

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Figure 5.- Three-second exposure through radial density filter on High Contrast Copy film.

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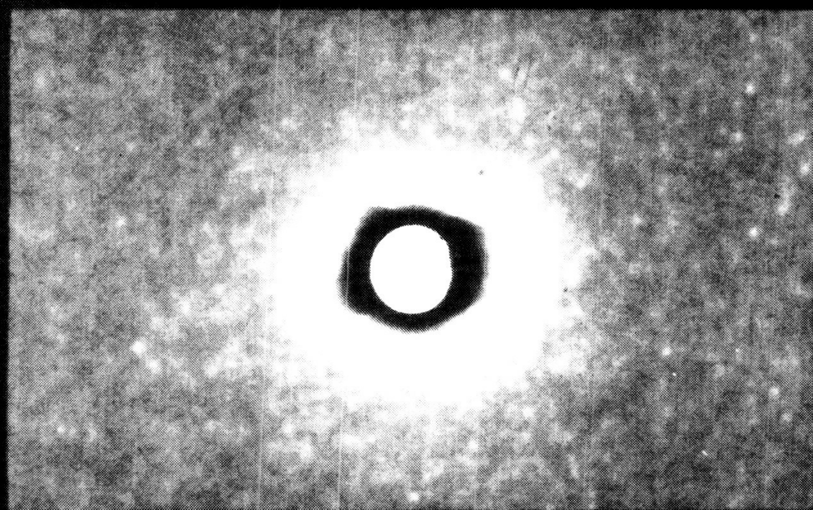
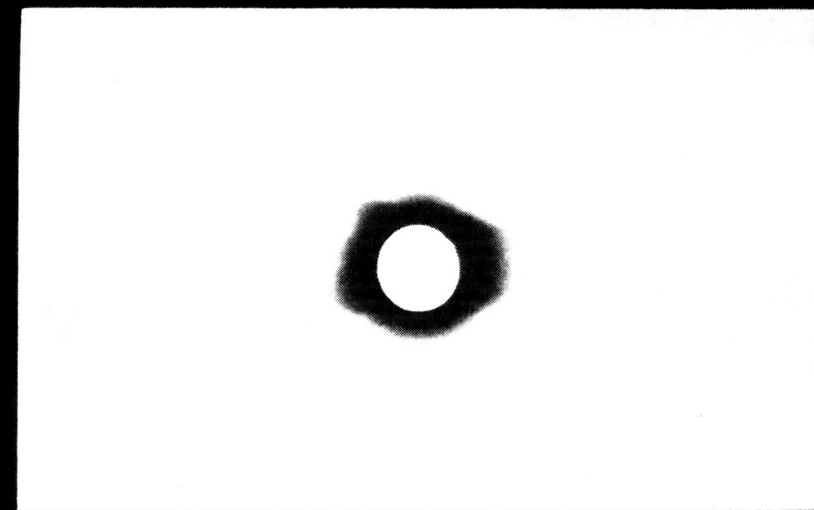
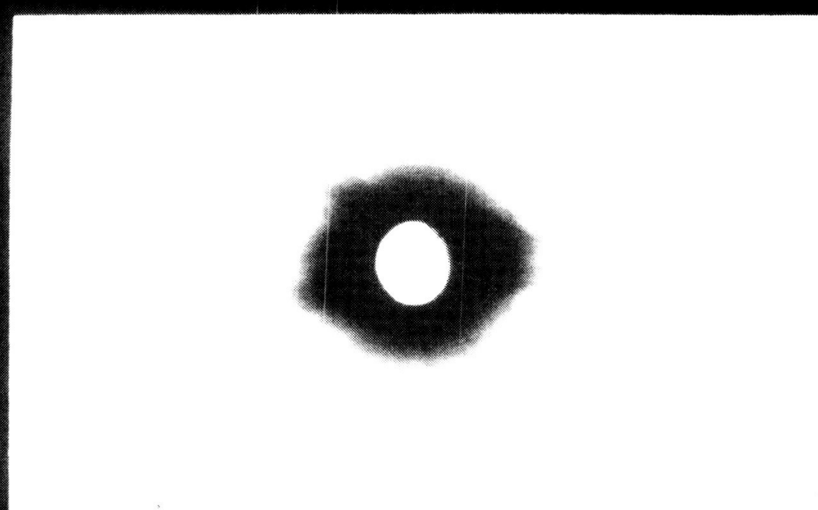


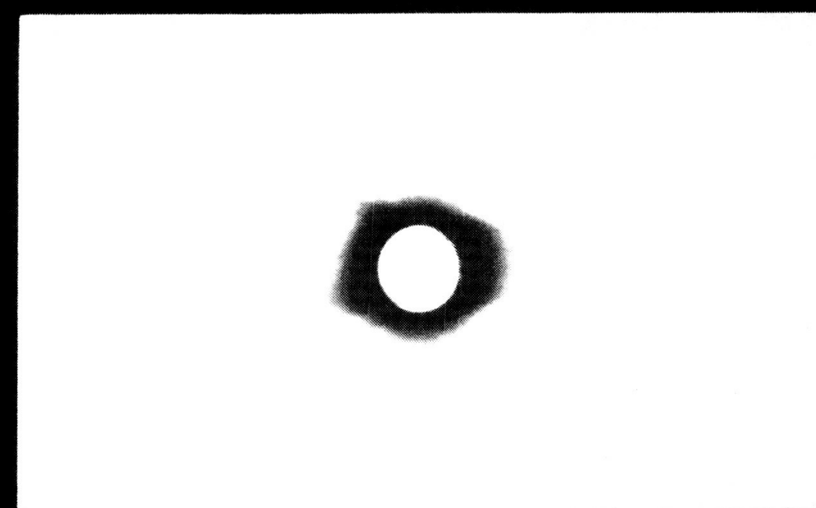
(a) 0.16-sec exposure; normally developed negative; print Fluor-O-Dodged with edge enhancement.



(b) 0.32-sec exposure; underdeveloped negative; Fluor-O-Dodged print.



(c) 0.16-sec exposure; overdeveloped negative; Fluor-O-Dodged print.



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(d) 0.64-sec exposure; underdeveloped negative; Fluor-O-Dodged print.

Figure 6.- Solar Corona, 20 July 1963.

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